

Full-Fledged Dwarf Irregular Galaxy Leo A¹

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ABSTRACT

We have studied Leo A – the isolated and extremely gas rich dwarf irregular galaxy of very low stellar mass and metallicity. Ages of the stellar populations in Leo A are ranging from ~ 10 Myr to ~ 10 Gyr. Here we report the discovery of an old stellar halo and a sharp stellar edge. Also we find the distribution of stars extending beyond the gaseous envelope of the galaxy. Therefore, Leo A by its structure as well as stellar and gaseous content is found to resemble massive disk galaxies. This implies that galaxies of very low stellar mass are also able to develop complex structures, challenging contemporary understanding of galaxy evolution.

Subject headings: galaxies:dwarf — galaxies:irregular — galaxies:individual(Leo A)
— galaxies:stellar content

1. Introduction

Understanding galaxy formation and evolution on the Hubble timescale is one of astronomy's greatest challenges. The importance of dwarf irregular galaxies (DIGs) and especially

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stellar populations in their outskirts for study of the galaxy build-up and star formation processes is well recognized and has been widely discussed recently, see e.g., Hodge (2003). DIGs are excellent targets to study galaxy evolution, as their long relaxation time makes them keep traces of interaction, merging event or starburst at least for a few billion years. Many studies (Minniti & Zijlstra 1996; Aparicio, Tikhonov, & Karachentsev 2000; Held et al. 2001; Drozdovsky, Tikhonov, & Schulte-Ladbeck 2003) were devoted to search for the outer stellar edges and extended old stellar populations in DIGs. The radial reddening of the stellar populations distributed in the disc-like structures was reported, however, the prominent edges were never revealed (Hodge 2003).

For our study we selected the nearby DIG Leo A (Fig. 1). Leo A is one of the most isolated galaxies in the Local Group. It is extremely gas rich (Young & Lo 1996), and possesses very low stellar mass (Mateo 1998) and metallicity (Skillman, Kennicutt, & Hodge 1989; van Zee, Skillman, & Haynes 1999). Basing on the Hubble Space Telescope (HST) photometric observations in the central part of the galaxy young age was deduced (Tolstoy et al. 1998). This conclusion challenged further investigations. Deep HST photometry was performed in the adjacent field, and the signatures of an old stellar population were identified (Schulte-Ladbeck et al. 2002). The final proof of the old stellar population in Leo A was brought by the discovery of the RR Lyr variables (Dolphin et al. 2002). Additionally, it was noticed that the red giant branch (RGB) stars are distributed more widely than the blue stars (Dolphin et al. 2002). Gaseous content of the galaxy was investigated in detail (Young & Lo 1996), and a symmetrical H I envelope twice more extended than the Leo A stellar distribution was discovered. Very small lopsidedness measured in the red continuum and in the H α emission (Heller et al. 2000) suggests that Leo A has not experienced any strong event of merger or interaction for at least a few billion years, and it is a good target for study of quiescent galaxy evolution.

2. Observations and Data Reductions

Taking into account the angular size of Leo A (the Holmberg’s dimension $\sim 7' \times 5'$) (Mateo 1998), Subaru Telescope equipped with Prime Focus Camera (Suprime-Cam) (Miyazaki et al. 2002) is an ideal instrument to study stellar content at the galaxy’s very outskirts (Fig. 1). Single shot Suprime-Cam mosaic (5×2 CCD chips) covers a field of $34' \times 27'$ (pixel size $0''.2 \times 0''.2$), and the magnitude of $V \sim 25^m$ is reached in 60 s. We acquired images in three broad-band filters: B (5×600 s), V (5×360 s) & I (30×240 s) during two photometric nights (seeing $< 0''.8$) on 2001 November 20-21. Standard reduction procedures were performed with a software package (Yagi et al. 2002) dedicated to the Suprime-Cam data. We employed

six central CCD frames of the mosaic, and performed crowded-field stellar photometry by applying DAOPHOT (Stetson 1987) implemented in the IRAF software package (Tody 1993) on 5 individual exposures in each photometric band. In order to use HST data for the central part of the galaxy consistently, we transformed instrumental magnitudes to the HST photometric system, $F439W$, $F555W$, $F814W$ (for abbreviation further we use B , V , I) by referring to the HST photometric data archive (Holtzman, Afonso, & Dolphin 2004). The transformation accuracy of $\sim 0^m.01$ in V - & I -bands, and of $\sim 0^m.02$ in B -band were achieved.

3. Results

In order to trace the entire extent of the old stellar populations in Leo A we employed the RGB stars. The following RGB star selection criteria have been applied: 1) location of stars in the color-magnitude diagram (CMD), I vs. $(V - I)$, within the zone marked in Fig. 2; 2) high photometric accuracy, $\sigma_I < 0^m.06$ & $\sigma_V < 0^m.08$; 3) good fit with the stellar point spread function (DAOPHOT parameters: $\chi^2 < 1.5$; $|\text{sharpness}| < 0.4$); 4) photometric criterion devoted to wipe out the objects with non-stellar spectra, $(B - V) - (V - I)$, in the range of $(-0.40) - (+0.10)$. The main parameters deduced for the RGB star distribution are: center at $\text{RA}(2000) = 09^h59^m24^s.0$, $\text{Dec}(2000) = 30^\circ44'47''$; ellipticity (ratio of semi-minor to semi-major axis) $b/a = 0.60 \pm 0.03$ coinciding with b/a of the H I envelope (Young & Lo 1996); position angle of the major axis $\text{PA} = 114^\circ \pm 5^\circ$. For detailed examination we selected the field located inside the ellipse ($b/a = 0.60$) of $a = 12'$ centered at the derived position (stellar content is shown in Fig. 2a), which is large enough to comfortably accommodate Leo A inside. We detected 1394 RGB stars distributed *symmetrically and smoothly* within this field. The average accuracies for the RGB star sample are: 1) coordinate matching among the B -, V - & I -bands, $0''.06$; 2) photometry, $\sigma_B = 0.019$ (4.6), $\sigma_V = 0.015$ (4.7), $\sigma_I = 0.010$ (4.7) (the average number of detections in each band is given in brackets).

The radial profile (RP) of the RGB star surface number density [arcmin^{-2}] (Fig. 3) was constructed by integrating within elliptical ($b/a = 0.60$) rings of a width, $\Delta a = 0'.5$ (at the Leo A distance, 800 kpc, $1'$ corresponds to 230 pc). We performed RP robustness tests by varying $b/a = (0.55, 0.60, 0.65)$, $\text{PA} = (104^\circ, 114^\circ, 124^\circ)$, and $\Delta a = 0'.2 - 1'.0$, as well as a magnitude at the faint limit, $I = (22.5, 23.0, 23.5)$, and found no significant change in the RP's form. Five distinct RP zones are noticeable (Fig. 3): 1) crowded central part, $a = 0'.0 - 2'.0$ (completeness at $I = 23^m$ varies with radius from 80 to 90%); 2) old exponential disk extending far beyond the previously estimated size of the galaxy (Mateo 1998), $a = 2'.0 - 5'.5$ (for representative stellar content see Fig. 2b), scale-length (S-L) $1'.03 \pm 0'.03$; 3) discovered new stellar component in DIGs, which we call “halo”, $a = 5'.5 - 7'.5$ (for stellar content

see Fig. 2c), S-L $1'.84 \pm 0'.09$; 4) sharp cut-off of the RGB star distribution coinciding with the observed edge (Young & Lo 1996) and predicted cut-off of the H I envelope (Sternberg, McKee, & Wolfire 2002), $a = 7'.5 - 8'.0$; 5) sky background zone where we derived a number density of contaminants to the RGB stars, $a = 8'.0 - 12'.0$ (for representative stellar content see Fig. 2d). In order to show the entire extent of the discovered structures in Leo A we over-plotted some characteristic size ellipses ($b/a = 0.60$) on the Suprime-Cam V -band image (Fig. 1). It is worth noting that the suspected Leo A RR Lyr variable C1-V01 (Dolphin et al. 2002) is located just outside the ellipse marking the galaxy size, confirming old age and large extent of the discovered stellar halo.

4. Discussion and Conclusion

In the Cold Dark Matter (CDM) cosmology scenarios galaxies are assumed to build up and develop their internal structure via hierarchical merging of the primordial amplified density fluctuations into larger systems. Therefore, our discovery of the stellar populations possessing distinct spatial distributions in the undisturbed very low mass DIG, Leo A, which is unlikely built via merging, suggests an alternative way of galaxy structure formation. In order to quantify the discovered stellar populations we estimate some of their basic parameters.

From the determined RP of the RGB stars it is straightforward to evaluate the total stellar mass of the old stellar population in Leo A. Assuming the Salpeter's initial mass function and a stellar mass range of $0.5 - 100 M_{\odot}$, we derived the mass of $\sim 4 \cdot 10^6 M_{\odot}$ (an isochrone by Girardi et al. (2002) of 10 Gyr and $Z = 0.0004$ has been employed). This is in agreement with the recent estimate (Lee, McCall, & Richer 2003) and confirms very low mass of the stellar populations in Leo A.

We performed a halo-disk RP decomposition considering two extreme cases: 1) when the exponential disk, S-L $1'.03$, is subtracted as the primary population, the remaining halo mass is $\sim 3\%$ of the disk mass; 2) when the exponential halo, S-L $1'.84$, is assumed to be a primary population, the halo mass is $\sim 30\%$ of the disk mass. The estimated lower and upper mass fractions of the halo are comparable to the Milky Ways halo and thick disk cases (Robin et al. 2003), respectively. The young (< 1 Gyr) disk population (stars located in CMD, $I < 24^m$ & $(V - I) < 0.25$, Fig. 2a) in Leo A is traceable up to the radius of a $\sim 5'$, and is exponentially distributed in the disk of S-L $0'.56 \pm 0.06$. The spatial distributions of the RGB stars and gas (Young & Lo 1996) possess sharp coincident cut-offs at large radius, implying that the disk properties of DIGs and of the massive galaxies (van der Kruit 2001) are similar.

We conclude, that the young and old Leo A disks together with the discovered old halo and sharp stellar edge closely resemble basic structures found in the large full-fledged disk galaxies. This suggests complex formation histories even in the very low stellar mass galaxies like Leo A, and challenges contemporary understanding of galaxy evolution.

We thank Alvio Renzini for a fruitful discussion and Jon Holtzman for advices on the use of his HST photometric data archive. V.V. acknowledges the National Astronomical Observatory of Japan for a professorship. This work was financially supported in part by a Grant-in-Aid for Scientific Research by the Japanese Ministry of Education, Culture, Sports, Science and Technology (No. 13640230), and by a Grant T-67/04 of the Lithuanian State Science and Studies Foundation.

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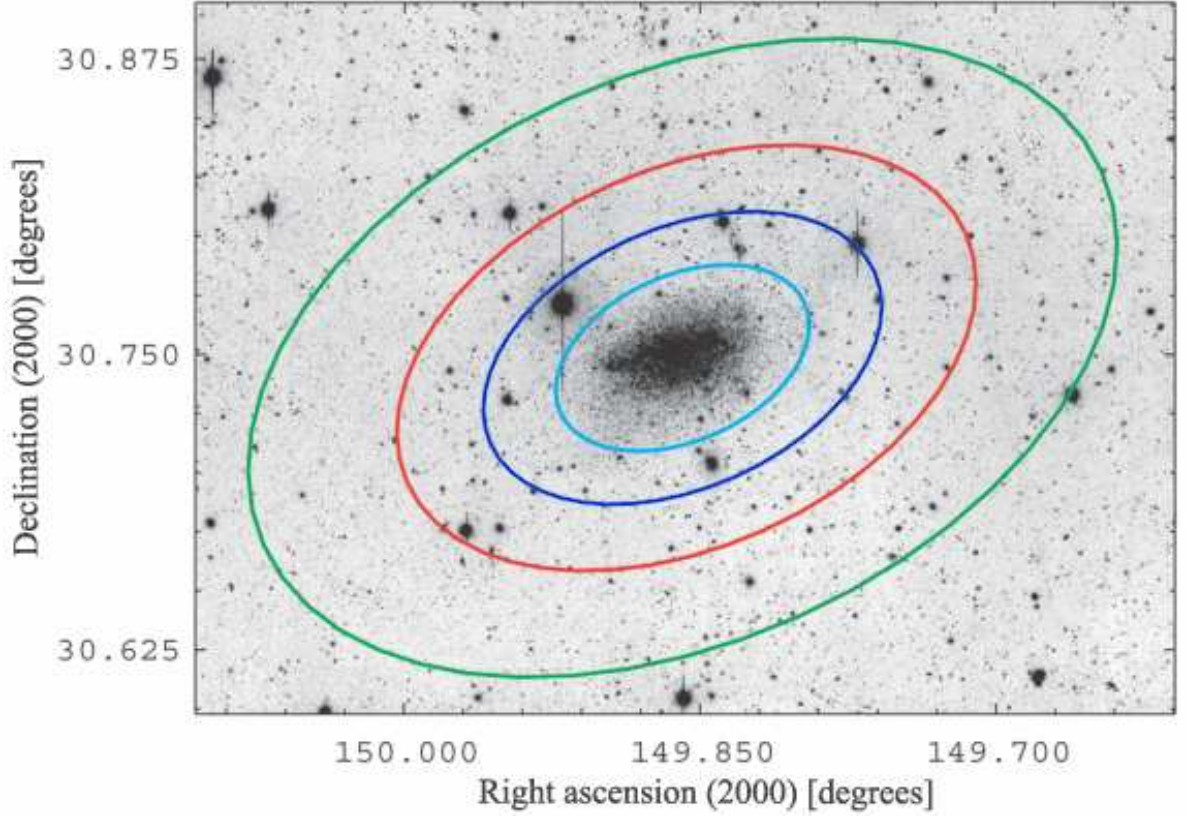


Fig. 1.— The Suprime-Cam V-band image of the galaxy Leo A. The ellipses ($b/a = 0.6$, a - semi-major axis) indicate: the Holmberg's radius ($B = 26^m.5 \text{ arcsec}^{-2}$), $a = 3'.5$ (cyan); the radial distance where the discovered halo becomes prominent, $a = 5'.5$ (blue); the size of Leo A established in this work, $a = 8'.0$ (red); the zone used for background source surface number density determination, $a = 12'.0$ (green).

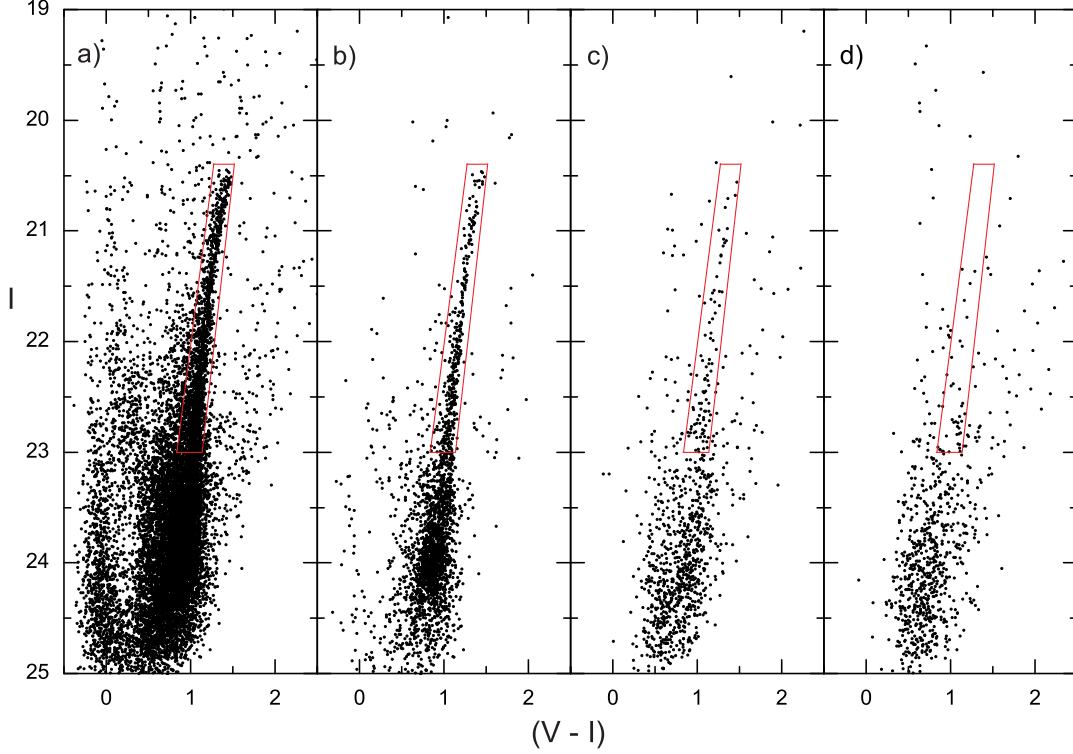


Fig. 2.— The color-magnitude diagrams of the stellar-like objects in Leo A. The objects are shown: (a) in the elliptical ($b/a = 0.6$) area, $a < 12'$, containing Leo A and its surroundings, the number of objects plotted, $N = 12,604$; (b) in the representative old disk area, $3'.0 < a < 5'.0$, $N = 2,462$; (c) in the discovered halo area, $5'.5 < a < 7'.5$, $N = 974$; (d) in the background area, $9'.0 < a < 10'.5$, $N = 780$. The RGB stars employed for the structure analysis of Leo A were selected from the zone marked by lines: magnitude ranges from the RGB tip $I = 20^m.4$ down to $I = 23^m.0$; the inclined lines are given by the equations $I = 31 - 7 \cdot (V - I)$ and $I = 28 - 6 \cdot (V - I)$.

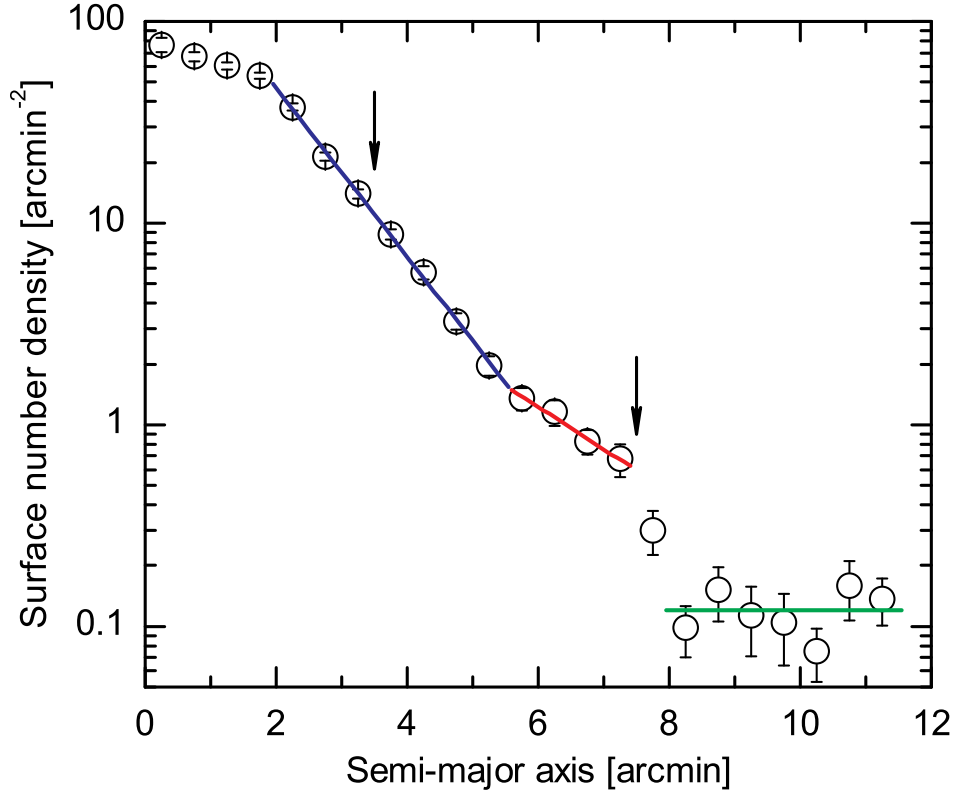


Fig. 3.— The radial profile of the RGB star surface number density in Leo A. The lines fitted to the old disk, $2'.0 < a < 5'.5$, and the halo, $5'.5 < a < 7'.5$, radial profiles, and the background, $8'.0 < a < 12'.0$ are shown. The Holmberg's radius ($a = 3'.5$) and the observed size of the H I envelope (Young & Lo 1996) ($a = 7'.5$) are indicated with arrows.